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FAST-SPECTRUM SPACE-POWER-REACTOR CONCEPTS USING BORON CONTROL DEVICES

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16. Abstract

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SUMMARY

Several fast-spectrum space-power-reactor concepts that use boron carbide control devices were examined to determine the neutronic feasibility of the design. The designs considered were

(1) A 199-fuel-pin, 12-poison-reflector-control-drum reactor

(2) A 232-fuel-pin reactor with 12 reflector drums and three in-core control rods

(3) A 337-fuel-pin design with 12 in-core control rods

(4) A 181-fuel-pin design with six drums closely coupled to the core to increase reactivity per drum

Adequate reactivity control and excess reactivity could be obtained for each concept, and the goals of 50 000 hours at 2.17 thermal megawatts with a lithium-7 coolant outlet temperature of 1222 K could be met without exceeding the 1-percent-clad-creep criterion. Heating rates in the boron carbide were calculated, but a heat-transfer analysis was not done. Such an analysis would be necessary as part of a materials compatibility and mechanical design study.

INTRODUCTION

Boron enriched in boron-10 is frequently considered for control of nuclear reactors because of its large neutron absorption cross section relative to fuel over almost the entire energy range of interest. Boron is used either as a passive burnable poison or in active control devices. For application in compact fast-spectrum reactors for space power systems, the two control devices most suitable are rotating control drums and axially moving control rods.

The desire for operation of the reactor at relatively high temperatures (approx 1100 to 1400 K) limits the use of boron to compounds capable of high-temperature stability and compatibility with structural materials. Such compounds as B_4C, HfB_2, ZrB_2, TaB_2, and $B_{13}C_2$ are candidates; and experimental work is being done on their high-temperature compatibility with other materials and on their thermal stability at the Lewis Research Center and at the Oak Ridge National Laboratory.

For the purposes of this report, neutronic calculations have been made using boron carbide (B_4C); these results should be applicable to first order to the other boron compounds as long as the amount of boron is the same.

Preliminary design calculations have been made for several reactor concepts which use enriched B_4C (92-percent ^{10}B) in control drums and in control rods for reactivity control. This report describes some of the characteristics of these concepts. Several design features are common to all the reactors; these features are discussed first before proceeding to the individual reactor concepts.

FEATURES COMMON TO REACTOR CONCEPTS CONSIDERED

The basic core structure is the same as that described in references 1 to 3. Uranium nitride (UN) fuel pins with a tungsten barrier and clad with the tantalum alloy T-111 are located in a honeycomb tube support lattice made of thin-walled T-111 tubes welded together (see fig. 1). The fuel pin diameter is 1.905 centimeters, and the center-to-center fuel pin spacing or pitch in the triangular lattice is 2.159 centimeters. The active coolant is lithium-7 (^7Li), and it flows in the annulus between honeycomb tube and fuel pin. Axial and radial reflectors are made from TZM, a high-molybdenum-content alloy. Performance goals are that the reactors be capable of producing 2.17 thermal megawatts for 50 000 hours with a ^7Li coolant outlet temperature of 1222 K. Over this lifetime, clad diametral creep should be 1 percent or less. The control system should be able to shut down the reactor with any two of the most important control elements stuck in their most reactive position. This results in a large total reactivity control requirement for the control system. An additional tentative design goal is that all control devices be designed for cooling by radiative heat transfer. Whether this design goal can be achieved will depend upon heat-transfer analyses, prevailing material temperatures, and the results of material compatibility studies. These design areas are outside the scope of this report though estimates of heating rates due to neutron and gamma interactions will be made.

12-DRUM, 199-PIN REACTOR CONCEPT

The first reactor concept is a common one in the sense that rotating control drums are located in a reflector region outside the reactor pressure vessel. Figure 2 shows a

30° sector of the reactor. The numbers corresponding to the honeycomb tubes are identification numbers for the fuel pins; the power distribution data are tabulated by pin number later (table III). The 12-control-drum, 199-fuel-pin design that was evolved results in a reactor diameter which will permit adequate control reactivity without an excessively long reactor.

Since drum cooling is to be by thermal radiation to surrounding materials, the immediate region around the drums is largely voided except for small reflector pieces of TZM near the pressure vessel. The effect of external shielding materials on control drum reactivity swing and total excess reactivity is limited by a lithium hydride (LiH) region deliberately located at the periphery of the reactor. The B_4C regions are annular sectors that are machine broached in the TZM drums. The web thickness between poison regions is 0.318 centimeter, the same as the distance between poison region and drum surface. Other drum designs could have been used, such as holes drilled in the TZM and filled with B_4C or tubes filled with B_4C and bundled together. Of course, any design considered should be able to accommodate enough B_4C for control requirements. The control drum diameter is 12.316 centimeters, which allows 0.25-centimeter clearance between drums and between drums and pressure vessel. The pressure vessel (Nb-1Zr) is 0.635 centimeter thick with an outside diameter of 35.81 centimeters. The reactor diameter is 61.51 centimeters out to the first LiH layer. The fuel length is 48.26 centimeters. The RZ calculational model (fig. 3) gives other pertinent dimensions. The material specifications used in the calculations appear in table I.

Table II itemizes the total reactivity and reactivity control requirements for the reactor. The temperature defect and long-term fuel swelling values are assumed to be the same as reported in reference 3. The calculated multiplication factor k includes a correction of -0.03 Δk for low-order transport calculation (S_4P_0 4-group) and one of -0.0078 Δk for $R\theta$ compared to xy calculations (ref. 3).

Figure 4 shows the reactivity control as a function of drum position. The curve has a $\sin^2 \theta/2$ shape which has been observed both experimentally (ref. 4) and from calculations of various types of drums (e.g., see ref. 3). The curve drawn fits the present calculated points quite well. The basis for these calculations is presented later. Estimated drum positions for the various conditions during reactor life are indicated. An additive contingency allowance of 1 percent $\Delta k/k$ to take care of cumulative uncertainties is assumed and included in the hot critical reactivity requirement. If the net uncertainty is less than 1 percent, the hot critical drum position would obtain at a larger drum position angle, and a corresponding shift in the other reactivity items would be made.

In addition to cases with the poison drums full in and full out, one of the calculations made was with the drums partially rotated. This case was studied to obtain estimates of the radial power distributions near hot critical and to obtain estimates of the ^{10}B burnup and neutron heating rates. Table III lists the radial power distribution data $P_r/\overline{P}_r$ for three different drum positions. The fuel pins are identified by number on figure 2. Pin 16 turns out to be the limiting pin with respect to the design criterion of a 1-percent limit on clad creep. The average power density is lower by about 4 percent for this reactor as compared to the 247-fuel-pin reactor in reference 3. However, the axial maximum-to-average power factor increased from 1.23 to 1.27. Thus, according to the creep-limit curve in reference 3, a radial power factor of ~0.97 should be acceptable for the limiting pin (pin 16) with 42-volume-percent fuel in a cell.

Volumetric average heating rates due to self-absorption of gamma rays and for the $^{10}B(n, \alpha)^{7}Li$ exothermic reaction have been calculated for the control drums in various positions (table IV). The maximum ^{10}B burnup within the control drums is also calculated. This quantity is obtained for the trailing edge of the B_4C poison region and averaged over life as the drums rotate from their initial hot critical position of 89^o to 180^o at the end of life. The maximum local burnup is 0.71 percent of the ^{10}B atoms, which occurs at the outside corner (trailing edge) of the poison sector at the axial center of the core. The 1.27-axial power factor is thus included.

These calculations were performed by using the ENDF/B, material 1009, neutron cross sections for ^{10}B; while those described in the following sections were done by using the older GAM-II cross sections for ^{10}B. Therefore, a quantitative comparison had to be made between the two sets of ^{10}B cross sections. This comparison had been made before (ref. 5) for a critical experiment and clearly indicated that the ENDF/B cross sections were the preferred set. For the present 199-pin, 12-drum concept, it was found that the reactivity control was reduced by about 10 percent and that the heating rates in the B_4C were about 5 percent lower when the GAM-II cross sections were used. The reactivity control difference was also observed in analysis of the critical experiment (ref. 5). Thus, these percentage discrepancies would probably be applicable to the control worth and heating rates discussed in the following sections; the values using GAM-II cross sections are reported, however. The differences calculated are traced to an underestimate of the $^{10}B(n, \alpha)^{7}Li$ cross section above about 80 keV in the older GAM-II evaluation that has been recognized and corrected for in the more recent ENDF/B evaluation.

232-FUEL-PIN, ROD-AND-DRUM-CONTROLLED REACTOR CONCEPT

The axially moving poisoned control rods used in this alternate reactor concept are provided to ensure sufficient reactivity control for designs with marginal reflector drum worth. These rods would normally be withdrawn and used only for scram purposes. The dry-well design envisioned complicates pressure vessel construction but eliminates the need for a sliding seal. Rod cooling would be by thermal radiation to the dry-well walls.

The calculated results for this reactor design are based on the GAM cross sections for ^{10}B and therefore are conservative by ~10 percent in reactivity control. However, heating rates due to the n, α reaction in ^{10}B may be underestimated by about 5 percent. These estimates are based on comparisons with calculations using ENDF/B, ^{10}B cross sections as described earlier.

Reactor Description

The rod and drum reactor uses the same fuel pin and honeycomb design as discussed previously though the fuel length was changed to 46.99 centimeters. The basic lattice consists of 253 honeycomb tubes, but 21 are removed in clusters of seven each to provide space for three rod wells. Thus, 232 fuel pins remain. Figure 5 shows a 60^{o} sector of the cross section of the reactor. Also shown are local-to-average power density ratios for each fuel pin; these are discussed later (see section Calculation Methods). Twelve control drums are used. The $^{10}B_4C$ poison material fits inside the areas indicated in figure 5. The drum design as shown has a smeared volume fraction of about 0.85 for the B_4C region and 0.15 for the 0.318-centimeter-thick TZM webs. If 70-percent-dense B_4C is assumed, the volume fraction of B_4C in the smeared drum sector is about 0.60. Alternate drum designs, such as drilled holes filled with B_4C, could be used as long as the volume fraction of B_4C remained about 0.60 and the nonpoison material volume fractions did not increase greatly beyond 0.15.

If a specified number of drums N are assumed to be closely spaced around the reactor with a specified clearance g between drums and between drums and pressure vessel, the following equation gives the drum diameter D_D:

$$D_D = \frac{(D_P + g)\sin\frac{\pi}{N}}{1 - \sin\frac{\pi}{N}} - g$$

where D_P is the outside diameter of the pressure vessel. The following table gives pertinent dimensions for a 40.132-centimeter-diameter pressure vessel, with 0.25-centimeter clearances for 8, 10, and 12 control drums:

Number of drums	Drum diameter, cm	Radius to drum center, cm	Reactor diameter, cm
8	24.780	32.710	90.708
10	17.805	29.223	76.759
12	13.848	27.244	68.844

The choice of 12 drums was based primarily on the relatively small reactor diameter obtained.

Clearance between the control drums and stationary TZM reflector pieces is 0.152 centimeter. Nb-1Zr with a thickness of 0.635 centimeter is used for the pressure vessel. The reactor length is 63.75 centimeters, which includes two 5.08-centimeter-thick end reflectors and distribution plenums. The control rod design is shown in cross section in figure 6.

Calculation Methods

Figure 7 shows the RZ calculational model. This model is used to determine the axial power density ratio; to determine the heating rates due to neutron capture in the ^{10}B at the rod tip; and, in conjunction with one-dimensional radial calculations, to determine the effective height to use in $R\theta$ calculations (based on fig. 5) to calculate transverse leakage rates. Four-energy-group GAM-II cross sections were used in the S_4P_0 transport-corrected approximation. $R\theta$ calculations were used to determine neutron heating rates in the $^{10}B_4C$ drum regions, the control reactivity due to the drums and due to the drums plus rods, the radial power density distributions, and the multiplication factor on which to base the excess reactivity. Corrections to the calculated k include -0.03 Δk for S_4P_0 4-group, instead of higher order, calculations and -0.0078 Δk for $R\theta$, instead of xy, geometry (ref. 3).

Heating rates in the $^{10}B_4C$ are based on 2.8-MeV-per-neutron capture, while gamma heating is estimated from calculations done by Gerald P. Lahti of the Lewis Research Center for a similar reactor.

Material specifications used in the calculations are given in table V. Note that three radial zones of fuel are given, corresponding to the zoning indicated on figure 5.

Results and Discussion

Table VI itemizes reactivity and control requirements for the rod-and-drum-controlled reactor. The allowance for long-term fuel swelling and for temperature defect are assumed to be the same as for the 199-pin, 12-drum reactor concept. The two-rod-stuck condition was used in the shutdown requirements because a rod is worth more than a drum (0.87 percent $\Delta k/k$ for a rod compared with 0.553 percent $\Delta k/k$ for a drum). Total control calculated is 2.16 percent $\Delta k/k$ more than required with two rods stuck; thus, adequate margin for calculational discrepancies exists. The required and calculated multiplication factors given in table VI can be compared directly since corrections have been made to the calculated k, as was noted in the discussion of calculation methods.

The maximum axial power density ratio $P_z/\overline{P}_z$ calculated from the RZ calculation is 1.24, which is approximately constant for each fuel pin. The radial power density ratios $P_r/\overline{P}_r$ are given in figure 5 for each fuel pin for both the drums-out (end of life) and drums-in conditions. With the fuel zoning used, which has 35.5-, 37.7-, and 42.0-volume-percent UN in inner (61 pins), middle (81 pins), and outer (90 pins) fuel zone cells, respectively, all fuel pins operate below the creep-limit criterion established in reference 3. A major factor contributing to this conservatism is the reduced power density of about 15 percent relative to the reactor in reference 3.

With a second iteration on the reactor design, it may be possible to reduce the reactor length somewhat by increasing the fuel loading in the core to offset the reactivity loss caused by length reductions. Drum control worth would be expected to decrease somewhat also. Heating rates in the B_4C have been calculated for several conditions, as presented in table VII. The beginning-of-life hot critical drum position is estimated at about 90° from shutdown; so the average heating rate at the beginning of life would be about 0.3 watt per gram of B_4C and would decrease through life to about 0.17 watt per gram of B_4C at the end of life. The maximum heating rate at the rod tip with the rod withdrawn, as shown in figure 3, is about 1.03 watts per gram of B_4C, which would remain fairly constant through life.

337-FUEL-PIN, ROD-CONTROLLED REACTOR CONCEPT

Since the applicability of poisoned control drums in the reflector depends upon the magnitude of radial neutron leakage from the core, there is an inherent limit on reactoı size at which drums cannot provide adequate reactivity control. In order to allow for the design of larger cores, a control system that is not so dependent on core size is desired. Moving fuel (in the form of rods or drums) and poisoned control rods could be used. The topic of this section is a reactor design concept using in-core control rods. The dry-well design discussed in the previous section is used to eliminate seal problems. The high heat-generation rate in $^{10}B_4C$ rods used in the core is of some concern since, at the anticipated high operating temperatures, containment of the boron carbide may be a major problem.

Reactor Description

The standard fuel pin design is retained without modification, as is the basic honeycomb structure within which the fuel pins fit. The honeycomb lattice is modified to the extent that wells for the control rods are created by omitting hexagonal clusters of seven tubes each and that the lattice size is increased to provide for 337 fuel pins and 12 control rod wells. A 60° sector of the reactor cross section is shown in figure 8. Details of the fuel pin lattice are given in figure 1; figure 8 shows only the gross honeycomb tube lattice. The radial reflectors are TZM. Average thickness is 8.43 centimeters, with a minimum thickness of 7.62 centimeters. The tantalum alloy (T-111) pressure vessel thickness is 0.635 centimeter, with an outside diameter of 65.02 centimeters.

As in the previous concepts, 5.08-centimeter-thick TZM (molybdenum) end reflectors are used. They are separated from the active core by the fuel pin ends, which contain crushable spacers (vibration suppressors) to provide for long-term fuel swelling; by the grid plates, which position the fuel pins within the honeycomb tubes; and by coolant distribution plenums. The total distance between the active core and the end reflector is 3.30 centimeters. Active core length is 37.59 centimeters. The fuel is uranium nitride with the uranium enriched to 93.2-percent uranium-235.

Figure 9 shows the control rod and well design that fits into the "holes" shown in figure 8. The 0.318-centimeter-thick rod pressure vessel is welded to the reactor pressure vessel at one end, thus forming the rod dry well, providing isolation of the control rod from the primary coolant, and eliminating all seals. Neutron and gamma heating in the control rod is radiated to the rod pressure vessel, which is cooled on the outside by primary coolant flowing between it and a flow splitter. The B_4C (with the boron enriched to 92-percent ^{10}B) form is not important for the neutronics calculations. It is assumed to be a porous solid with a density of 0.7 of that readily obtainable, which is about 2.44 grams per cubic centimeter.

Two radial fuel zones are used; the outermost 156 pins contain 42.0-volume-percent UN in each fuel cell, while the remainder contain 38.5 volume percent. The average volume percent of fuel in a cell is 40.0. The power density is relatively low in this reactor, and additional fuel could be added without exceeding the creep limit of 1 percent diametral growth of the fuel pin clad. In fact, the calculations indicate that an additional

0.8-volume-percent UN may be required. Alternatively, a 2-centimeter increase in fuel length could be used. Neither of these changes would significantly alter the results of this study.

Calculation Methods

The quantities emphasized in the calculations in this section include axial and radial power density distributions, reactivity control swing, and effective multiplication factors to establish fuel loading requirements. Neutron heating rates in the B_4C are also calculated. Gamma heating in the control rod is estimated from unpublished calculations by Gerald P. Lahti of this laboratory for a reactor similar to the fueled-drum reactor in reference 3. The gamma heating values were scaled by the average power density ratio of the two reactors.

Basically, two types of spatial calculations are performed - RZ and $R\theta$. An RZ model as shown in figure 10 is used to account for the effect of the end reflectors, one of which has rod penetrations. In establishing the RZ model, which requires azimuthal symmetry, the following steps were taken:

(1) The fueled volume is based on the unit cell.

(2) The radius to the center of each boron carbide annulus representing six rods is the same as the corresponding radii to the rod centers in figure 8. The rod sheath volume is equal on each side of a boron carbide annulus. With the rods inserted the rod clad is smeared in with the rod sheath. The lithium-7 outside the rod sheath which does not belong to fuel cells is also incorporated.

The densities and volume percents of each constituent of each region as given in table VIII allow calculation of the atom densities of each region in figure 9. Table VIII also contains information concerning the $R\theta$ calculational model based on figure 8; $R\theta$ is the second type of spatial calculation performed. With θ equal to 30° a good representation of the geometry is obtained with 43 radial and 30 angular mesh intervals.

The $R\theta$ calculational model is a better representation of the reactor cross section than the RZ model and is used to obtain the control swing and radial power density distributions. The DOT-II W program is used for the four-energy-group spatial calculations. The GAM-II program is used to obtain spectrum-averaged cross sections. Four neutron energy groups were used with lower energy cut-points at 0.821, 0.183, 40.9×10^{-3}, and 0.414×10^{-6} MeV. The upper energy bound is at 14.9 MeV.

Results and Discussion

Excess reactivity and control requirements. - Table IX itemizes pertinent quantities related to the reactivity and reactivity control of the rod-controlled reactor. The temperature defect and long-term fuel swelling reactivity values are assumed to be the same as previously. The fuel swelling value is conservative since the power density for the rodded core is lower than for the reactor in reference 3 (0.0424 against 0.0579 MWt per liter of fuel cells).

The reactivity worth of 12 control rods is 0.65 percent $\Delta k/k$; the inner six are worth 5.30 percent $\Delta k/k$, while the outer six are worth 4.35 percent $\Delta k/k$. The worth of two inner rods is assumed for the two-rod-stuck shutdown criterion. Estimated control required is 6.63 percent $\Delta k/k$; hence, 3.02-percent-$\Delta k/k$ extra control exists. This means that the rods at hot critical will not be inserted very far into the core, thus reducing the total heating rate in the rods (~1.46 W/g, see table X).

The required multiplication factor of 1.0402 is 1.00 percent Δk larger than computed for this reactor. This amount of reactivity can be made up by increasing the average fuel loading by about 0.8 volume percent UN in the average core loading or by increasing the length of fuel by about 2 centimeters. A combination of these methods could also be used. Another alternative is to reevaluate the excess reactivity requirements by detailed calculations for the temperature-defect, long-term fuel swelling, and contingency requirements. For the purpose of this study, however, the results that follow on power distributions and heating rates in the rods are based on the data in table IX. Only minor changes would be expected in these data with any of the proposed "fixes" for the multiplication factor.

Figure 11 shows a typical control curve for the reactor with estimates of the rod positions at hot critical, at cold critical, and at shutdown with two inner rods stuck. In addition to the end points, two calculated points for intermediate rod positions are shown. These calculated points are in reasonable agreement with the theoretical $\sin^2(\pi L/2L_0)$ curve, where L_0 is the core length and L is the rod bank position.

Power density distributions. - Figure 12 shows the axial power density ratio $P_z/\overline{P}_z$ for the rods at hot critical position. Note that the $P_z/\overline{P}_z$ at the rod tip is about 1.0 and that the rods have a relatively short travel to end of life. The use of high-worth rods that are not operating in the high-heat-generation regions of the core should be a definite advantage in keeping rod temperatures down. The axial power distribution symmetry is not greatly disturbed by the rod bank even at hot critical bank position; symmetry would tend to be gradually restored as the end of life approached.

Figure 13 shows radial power density ratios $P_r/\overline{P}_r$ for various rod configurations. The upper part of figure 13(a) is for all rods inserted, while the lower part is for all rods withdrawn. Figure 13(b) shows two situations in which the rods are operated as either an inner or outer group of six rods. The $P_r/\overline{P}_r$ in any pin in any of these configurations is well below the allowable value that would result in 1 percent creep in the fuel pin clad.

Heating rates in rod material at hot critical. - Table X gives heating rates due to neutrons and gamma rays in the rod materials for the inner rods. The neutron heating is primarily in the B_4C, while the gamma heating would apply to the rod cladding as well as to the B_4C. The values in the table are for specific points in the rod, specifically the maximum (rod tip) and minimum values within the active part of the core. Intermediate values or axial average values can be obtained with reference to figure 12. The heating rates would follow the $P_z/\overline{P}_z$ shape. The heating rates in the outer rods would be about 7 percent lower than the values in table X. Maximum burnup is about 1 percent of the ^{10}B atoms in the first centimeter at the rod tip of the inner rods.

181-FUEL-PIN, CLOSELY-COUPLED-POISON-DRUM REACTOR CONCEPT

The worth of poisoned control drums can be increased by closely coupling the control drums into a higher importance region of the reactor. Usually, one thinks of increasing the length-diameter ratio of the core so the distance from the center of the core to the drums is decreased. A more novel way is shown in figure 14, in which the drums fit between the star points; that is, the drums are indented into the core. The geometry is quite similar to that of the experiments discussed earlier (ref. 5). The drums are located in their individual pressure vessel dry wells of Nb-1Zr, and the entire reactor is enclosed in a pressure vessel. High drum reactivity worth can be obtained but at the expense of relatively high heat-generation rates. Figure 14 shows a 30° sector of the core, along with radial power distributions for both the poison-out and poison-in conditions. Also indicated are the fuel volume percents of cells used in power-tailoring the reactor. Active fuel length is about 53.3 centimeters so that, though there are only 181 fuel pins, the power density is similar to the reactor in reference 3.

Reactivity worth of the control drums as shown in figure 14 is 10.2 percent $\Delta k/k$, more than adequate. The average $^{10}B(n,\alpha)^{7}Li$ reaction heating rate for the poison fully in is 0.67 watt per gram of B_4C; for the poison fully out it is 0.25 watt per gram of B_4C. At the beginning of life with the drums at 120° out, the heating rate would be 0.4 watt per gram of B_4C. A limited amount of design work was done on this concept.

SUMMARY COMPARISON OF REACTOR CONCEPTS

The four reactor concepts are compared in table XI. The number of fuel elements, control elements, and dimensions are given. From the preliminary analysis of these concepts, each appears neutronically acceptable for the performance goals established for this study. With only minor changes required, each has enough excess reactivity and reactivity control. Power-tailoring allows even the worst pin in each reactor to operate without exceeding the 1-percent-clad-creep limit over the core design life of 50 000 hours.

CONCLUDING REMARKS

Several fast-spectrum space-power-reactor concepts that use boron carbide control devices were examined to determine the neutronic feasibility of the designs. The designs considered were

(1) A 199-fuel-pin, 12-poison-reflector-control-drum reactor
(2) A 232-fuel-pin reactor with 12 reflector drums and three in-core control rods
(3) A 337-fuel-pin design with 12 in-core control rods
(4) A 181-fuel-pin design with six drums closely coupled to the core to increase reactivity per drum

Adequate reactivity control and excess reactivity could be obtained for each concept, and the goals of 50 000 hours at 2.17 thermal megawatts with a lithium-7 coolant outlet temperature of 1222 K could be met without exceeding the 1-percent-clad-creep criterion. Heating rates in the boron carbide were calculated, but a heat-transfer analysis was not done. Such an analysis would be necessary as part of a materials compatibility and mechanical design study.

Lewis Research Center,
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TABLE I. - MATERIAL SPECIFICATIONS FOR RZ AND Rθ MODELS OF 12-DRUM, 199-PIN REACTOR CONCEPT

Material	Density, g/cm^3	Fuel zones			Lithium gap	Pressure vessel	Radial reflector	Poison region	Shield	Plenum	Axial reflector
		I	II	III							
							Material content, vol. %				
UN[b]	14.2	35.5	37.7	42.0	-----	-----	----	----	----	----	-----
^7Li	.516	25.2	25.2	25.2	100.0	-----	----	----	10.0	47.0	7.85
Nb-1Zr[c]	8.4	----	----	----	-----	100.0	----	----	----	----	-----
T-111[d]	16.72	24.4	24.4	24.4	-----	-----	----	----	----	33.0	-----
TZM[e]	10.2	----	----	----	-----	-----	92.0	20.3	15.0	----	92.15
B_4C[f]	2.44	----	----	----	-----	-----	----	33.0	----	----	-----
W	19.3	1.5	1.5	1.5	-----	-----	----	----	----	----	-----

[a]For Rθ calculation, poison region is 14.4 vol. % Mo, 60 vol. % B_4C.
[b]93.2 Percent enriched in ^{235}U.
[c]Treated as 100-percent Nb.
[d]Ta - 8.5-wt. % W - 2.3-wt. % Hf.
[e]Treated as 100-percent Mo.
[f]92 Percent enriched in ^{10}B.

TABLE II. - EXCESS REACTIVITY AND CONTROL REQUIREMENTS FOR 12-DRUM, 199-PIN REACTOR CONCEPT

[Required multiplication factor k, 1.047; calculated multiplication factor k, 1.055; excess multiplication factor available Δk, 0.008.]

	Reactivity, percent $\Delta k/k$
Uranium-235 atom destroyed (2.86 at. % average)	1.43
Long-term fuel swelling	.95
Temperature defect	1.09
Contingency allowance	1.00
Excess reactivity required	4.47
Shutdown	1.00
Two-drum-stuck shutdown	1.12
Total control reactivity	6.59
Calculated control reactivity	6.71
Excess control available	.12

TABLE III. - 12-DRUM, 199-PIN-REACTOR LOCAL-TO-AVERAGE RADIAL POWER DISTRIBUTIONS FOR THREE CONTROL DRUM POSITIONS

Zone	Fuel pin number[a]	Poison out	Poison 75° out	Poison in
		Radial power distribution, $P_r/\overline{P}_r$		
1	1	1.19	1.25	1.30
	2	1.18	1.23	1.29
	3	1.16	1.21	1.26
	4	1.15	1.20	1.24
	5	1.12	1.16	1.20
	6	1.10	1.14	1.18
	7	1.07	1.10	1.12
2	8	1.12	1.15	1.20
	9	1.09	1.12	1.13
	10	1.06	1.08	1.10
	11	1.04	1.05	1.06
	12	1.00	1.02	1.02
	13	1.00	.97	1.00
	14	.97	.97	.97
	15	.94	.93	.93
3	16	0.97	0.96	0.94
	17	.97	.95	.92
	18	.94	.94	.89
	19	.91	.88	.85
	20	.84	.77	.75
	21	.86	.81	.78
	22	.84	.79	.77
	23	.82	.76	.72

[a]See fig. 2 for fuel pin identification numbers.

TABLE IV. - AVERAGE HEATING RATES IN POISON REGION OF CONTROL DRUM FOR 199-PIN, 12-DRUM REACTOR CONCEPT

[$R\theta$ four-group S_4P_0 calculation with ENDF/B boron-10 cross sections.]

Condition	Neutron heating, W/g B_4C	Gamma heating, W/g
Poison fully out	0.23	0.03
Poison 75° out	.39	.08
Poison fully in	.44	.10

TABLE V. - MATERIAL SPECIFICATIONS FOR RZ MODEL OF ROD-AND-DRUM-CONTROLLED REACTOR CONCEPT

[For Rθ model, drum poison is 59.96-vol.% B_4C - 14.35-vol.% TZM; rod sheath for rods-out case is 34.88-vol.% T-111 - 3.71-vol.% ^7Li; all other regions are same as for RZ model.]

Material	Density, g/cm^3	Fuel zones			Lithium gap	Rod poison	Drum poison	Pressure vessel	End reflector	Radial reflector	Plenum	Shield	Rod sheath
		Inner	Middle	Outer									
		Material content, vol. %											
UN[a]	14.2	35.5	37.7	42.0	-----	----	-----	-----	-----	-----	----	----	------
T-111[b]	16.72	24.4	24.4	24.4	-----	----	-----	-----	-----	-----	33.0	----	0.4824
Nb-1Zr	8.4	----	----	----	-----	----	-----	100.0	-----	-----	----	----	------
^7Li	.516	25.2	25.2	25.2	100.0	----	-----	-----	7.85	-----	47.0	10.0	.0513
TZM[c]	10.2	----	----	----	-----	----	49.77	-----	92.15	94.42	----	15.0	------
B_4C[d]	2.44	----	----	----	-----	70.0	33.4	-----	-----	-----	----	----	------
LiH	.8	----	----	----	-----	----	-----	-----	-----	-----	----	70.0	------
W	19.3	1.5	1.5	1.5	-----	----	-----	-----	-----	-----	----	----	------

[a]93.2 Percent enriched in ^{235}U.
[b]8.5-Wt.% W - 2.3-wt.% Hf - 89.2-wt.% Ta.
[c]Treated as Mo.
[d]92 Percent enriched in ^{10}B.

TABLE VI. - EXCESS REACTIVITY AND CONTROL REQUIREMENTS

FOR ROD-AND-DRUM-CONTROLLED REACTOR CONCEPT

[Required multiplication factor k, 1.056; calculated multiplication factor k, 1.057.]

	Reactivity, percent $\Delta k/k$
Uranium-235 atom destroyed (2.62 at. % average)	1.31
Long-term fuel swelling	.95
Temperature defect	1.09
Contingency allowance	1.00
Excess reactivity	4.35
Shutdown	1.00
Two-rods-stuck shutdown	1.74
Total control required	7.09
Excess control calculated	2.16
Total control calculated	9.25

TABLE VII. - HEATING RATES IN B_4C

Model	Condition	Neutron heating, W/g B_4C	Estimated gamma heating, W/g	Location and type of heating calculation
Rθ	Drums in Rods out	0.353	0.06	Average in poison region of drums
Rθ (end of life)	Drums out Rods out	.164	.01	Average in poison region of drums
RZ	Drums out Rods out	.984	.05	Maximum at rod tip

TABLE VIII. - MATERIAL SPECIFICATIONS FOR RZ MODEL OF ROD-CONTROLLED REACTOR CONCEPT

[Rθ materials are the same except for rod sheaths and explicit ^{7}Li region, but end reflectors and plenum are not used.]

Material	Density, g/cm^3	Core fuel cells		Control rods					Side reflector	End reflector	Plenum	Lithium gap	Pressure vessel
		Zone 1	Zone 2	Sheath				Poison					
				Rods in		Rods out							
				Rz	Rθ	Rz	Rθ						
		Material content, vol. %											
UN[a]	14.2	38.5	42.0	-----	-----	----	----	--	--	----	--	---	---
T-111[b]	16.72	24.4	24.4	40.5	58.5	28.5	41.3	--	--	----	33	---	100
W	19.3	1.5	1.5	.67	.97	----	----	--	--	----	--	---	---
^{7}Li	.516	25.2	25.2	34.9	6.1	54.9	6.1	--	--	7.8	47	100	---
MO	10.2	----	----	-----	-----	----	----	--	98	92.2	--	---	---
B_4C[c]	2.44	----	----	-----	-----	----	----	70	--	----	--	---	---

[a]93.2 Percent enriched in ^{235}U.
[b]Ta - 8.5-wt.% W - 2.3 wt.% Hf.
[c]92 Percent enriched in ^{10}B.

TABLE IX. - EXCESS REACTIVITY AND CONTROL REQUIREMENTS

FOR ROD-CONTROLLED REACTOR CONCEPT

[Required multiplication factor k, 1.040; calculated multiplication factor k, 1.030; additional multiplication factor needed Δk 0.010.]

	Reactivity, percent $\Delta k/k$
Uranium-235 atom destroyed (2.2 at. % average)	1.05
Temperature defect (460 to 1222 K)	1.09
Long-term fuel swelling	.95
Contingency	.77
Excess reactivity required	3.86
Shutdown by 1 percent	1.00
Two-inner-rods-stuck shutdown	1.77
Control required	6.63
Control calculated (inner rods, 5.30 % $\Delta k/k$, outer rods, 4.35 % $\Delta k/k$)	9.65
Extra control margin	3.02

TABLE X. - HEATING RATES AT HOT CRITICAL ROD POSITION FOR

INNER RODS FOR ROD-CONTROLLED REACTOR CONCEPT

Position	Neutron heating, W/g B_4C	Gamma heating, W/g
Inner rod tip	1.25	0.21
Outer rod tip	1.17	.16
Inner rod at end reflector	.59	.15
Outer rod at end reflector	.55	.11

TABLE XI. - COMPARISON OF REACTOR CONCEPTS

	Reactor concept			
	Twelve drum	Rod and drum controlled	Rod controlled	Indented drum
Number of fuel elements	199	232	337	181
Active fuel length, cm	48.26	46.99	37.59	53.34
Reactor outside diameter, cm	61.51	68.84	65.0	59.69
Reactor length including end reflectors	65.02	63.75	54.4	70.1
Number of rods	-----	3	12	-----
Number of drums	12	12	-----	6
Rod diameter, cm	-----	5.32	5.32	-----
Drum[a] diameter, cm	12.32	13.85	-----	14.99

[a]Diameter equivalent to removal of seven-pin cluster.

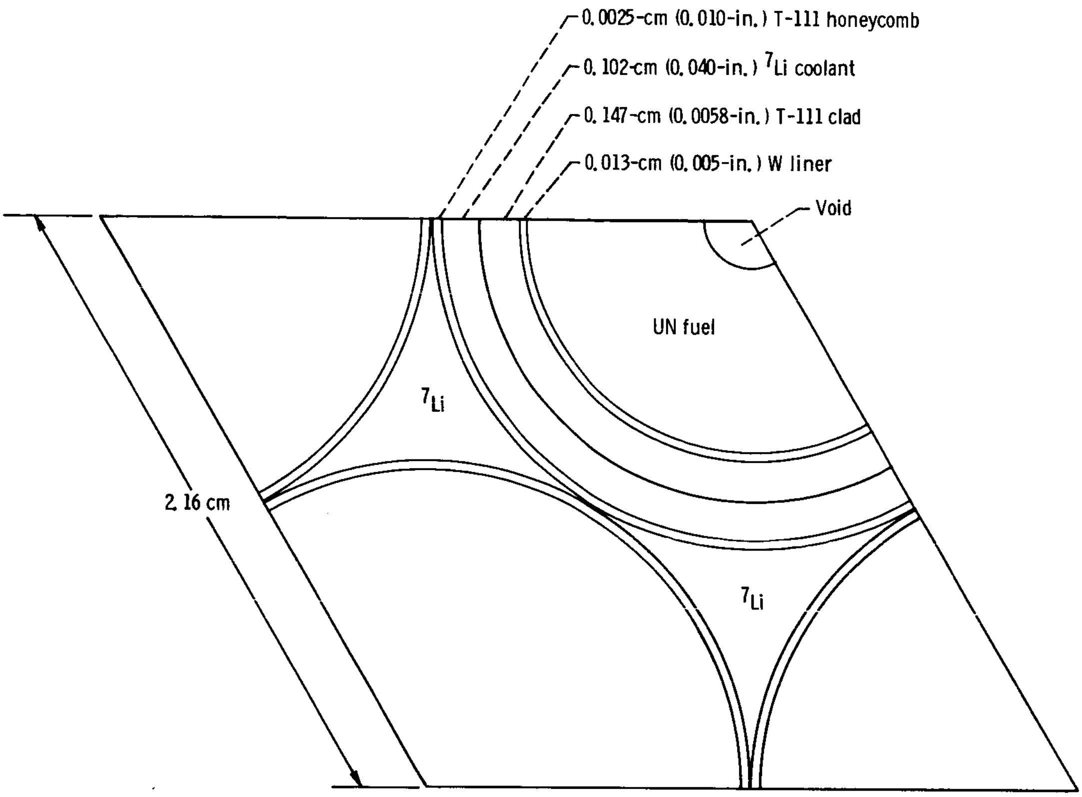


Figure 1. - Cell and fuel pin geometry.

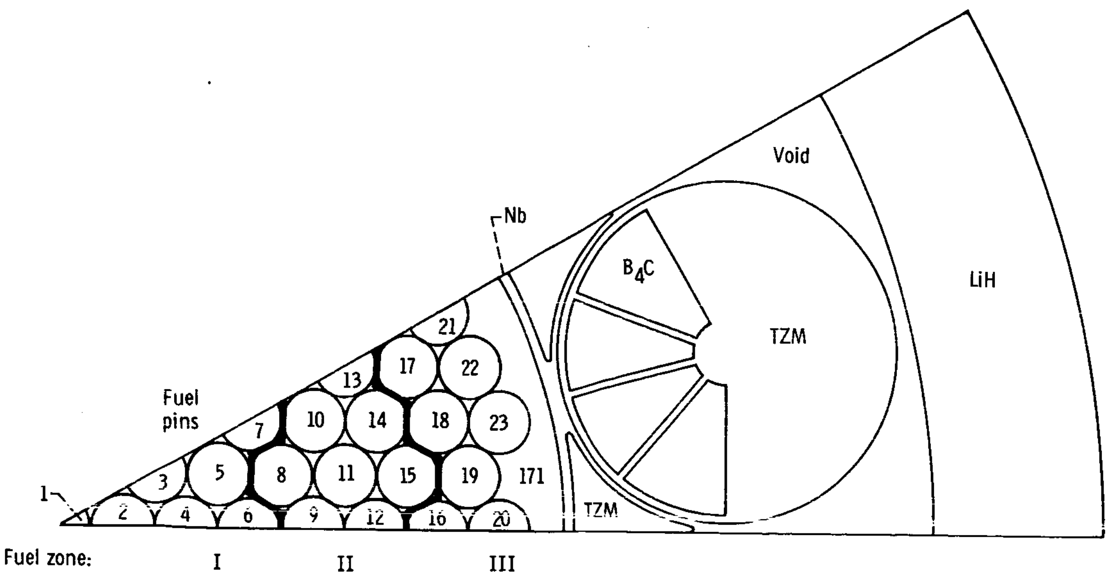


Figure 2. - 30° Sector of cross section of 199-pin, 12-drum reactor. Multiplication factor, 1.055; control reactivity, 6.71 percent $\Delta k/k$; fueled length, 48.3 centimeters; pressure vessel diameter, 35.8 centimeters; drum diameter, 12.3 centimeters.

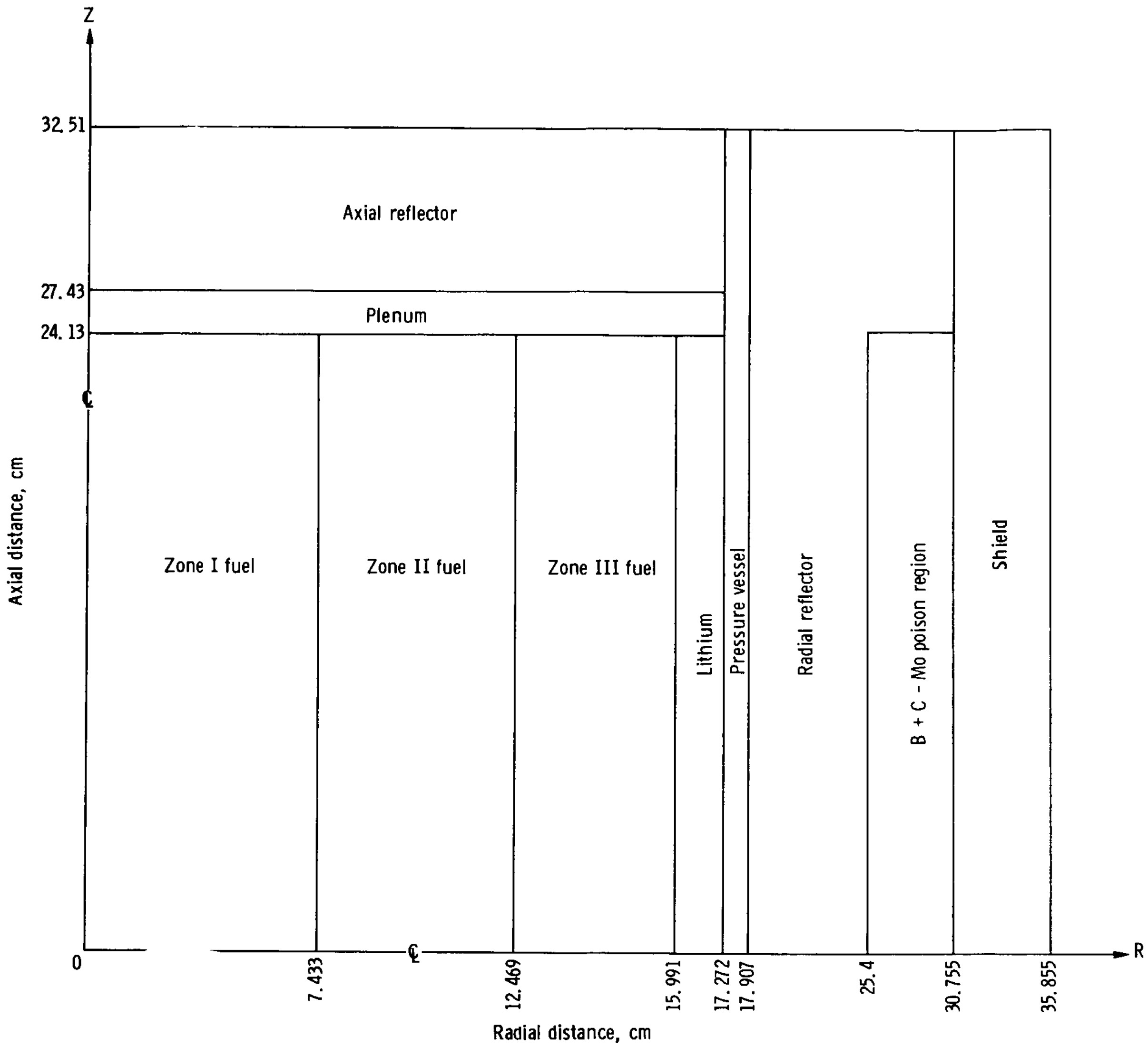


Figure 3. - RZ calculational model for 12-drum, 199-pin reactor concept.

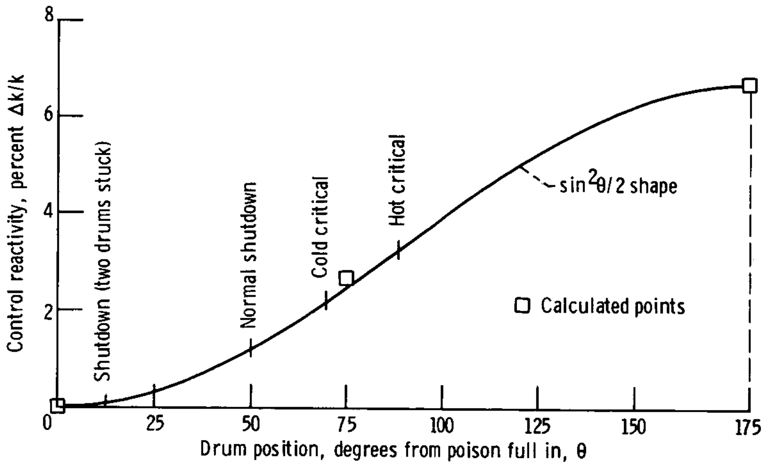


Figure 4. - Reactivity control characteristics at beginning of life for 12-drum, 199-pin reactor concept.

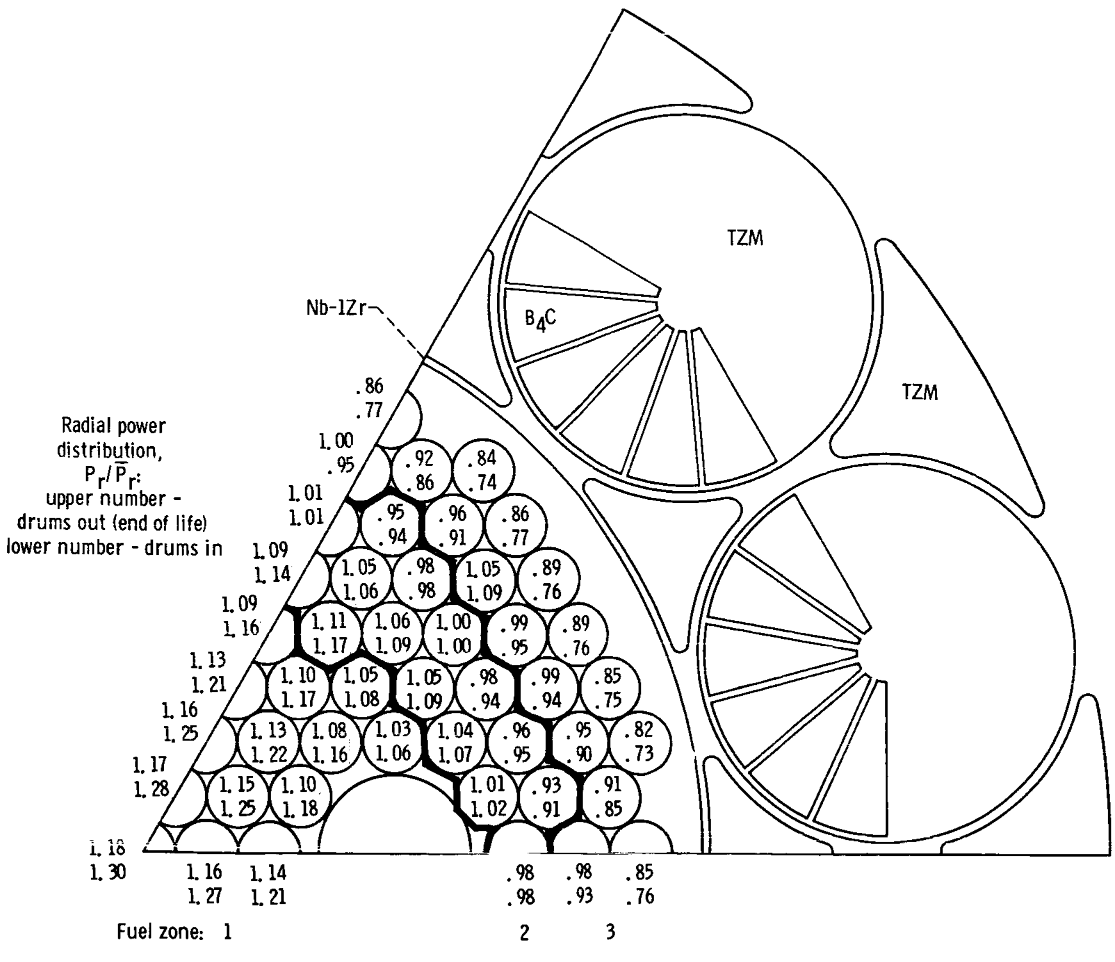


Figure 5. - 60° Sector of cross section of rod-and-drum-controlled reactor.

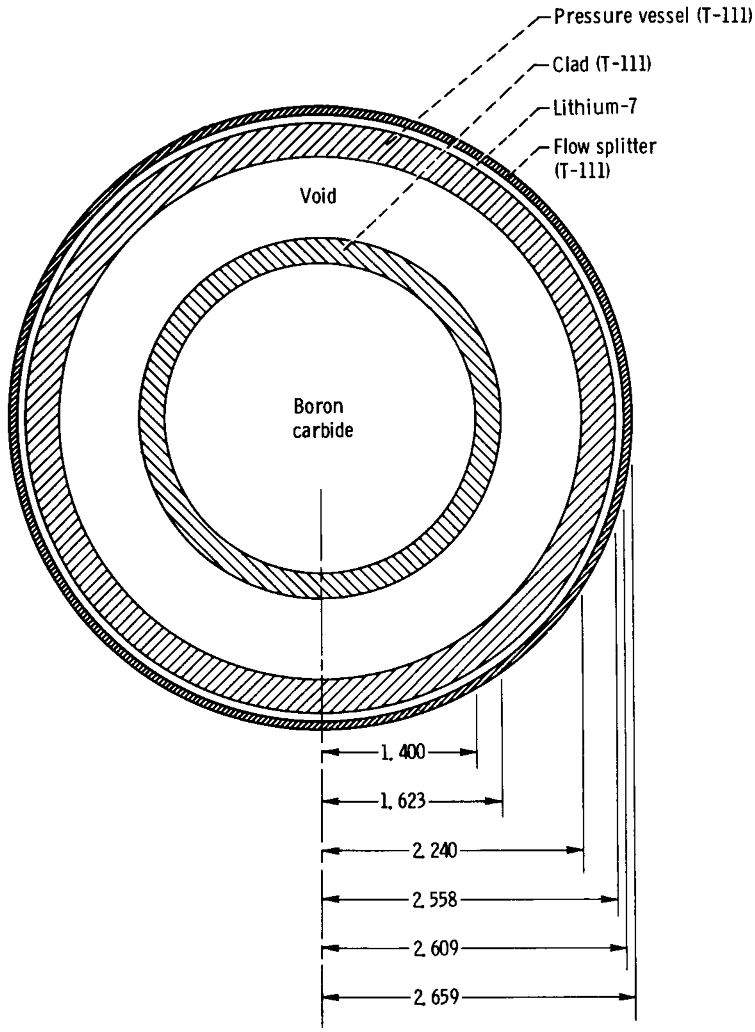


Figure 6. - Cross section of rod and rod well for rod-and-drum-controlled reactor. (Scale, x1$\frac{1}{2}$, dimensions are in centimeters.)

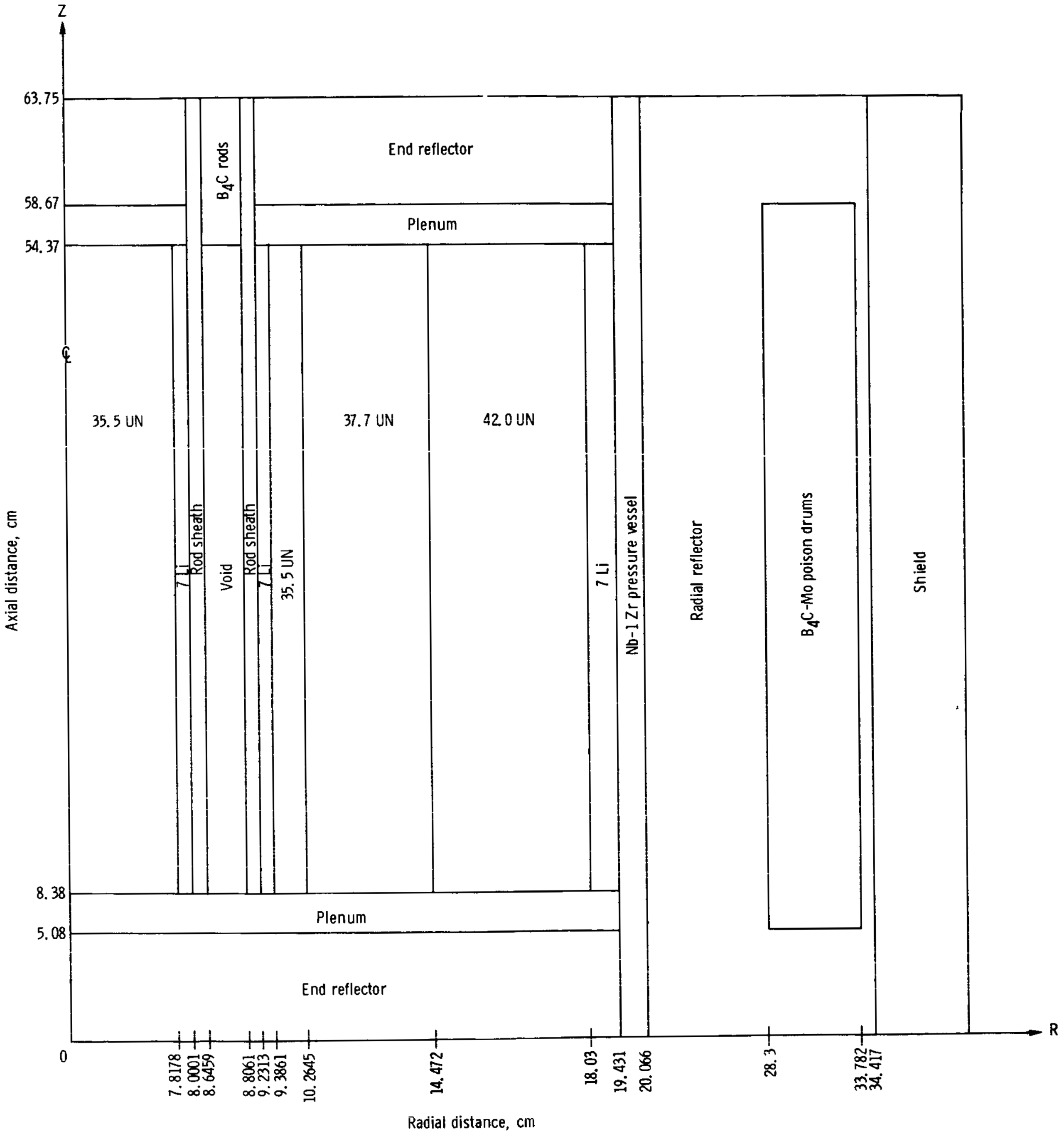


Figure 7. - RZ calculational model of rod-and-drum-controlled reactor.

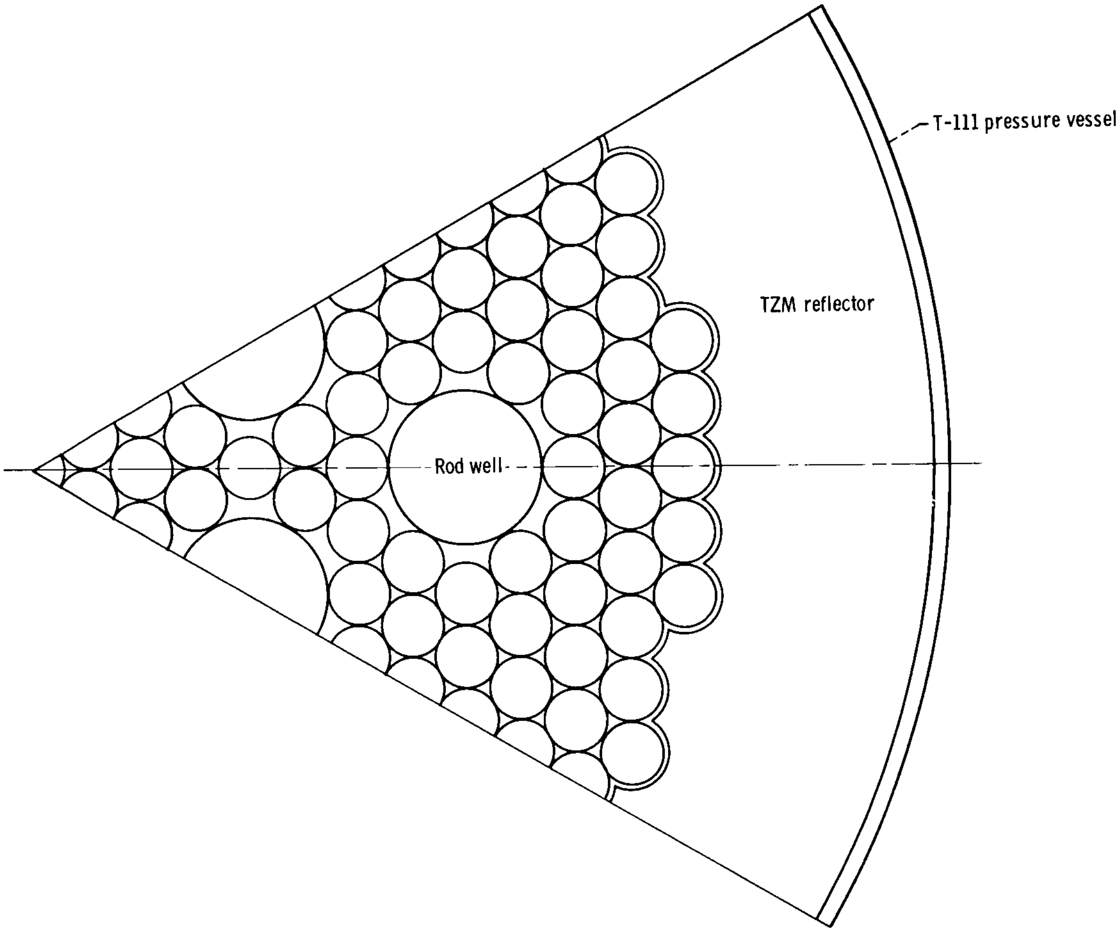


Figure 8. - 60° Sector of cross section of 12-rod, 337-pin rod-controlled reactor. Diameter, 65 centimeters (25.6 in.).

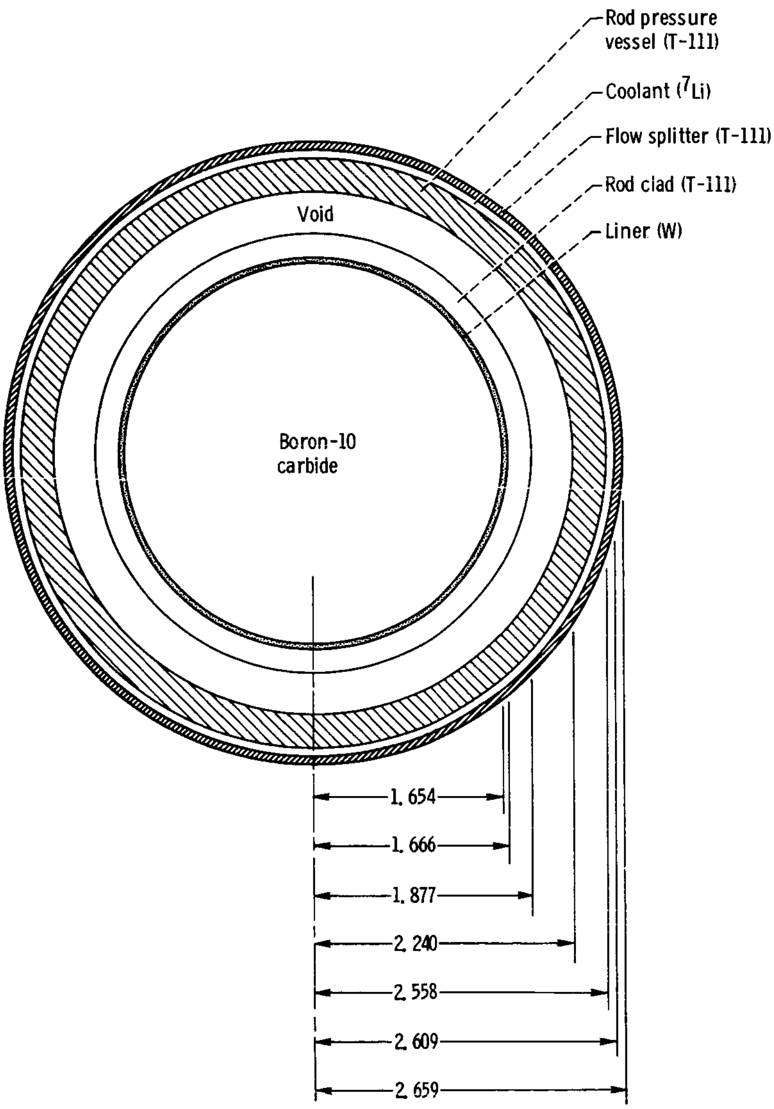


Figure 9. - Cross section of rod and rod well for 12-rod, 337-pin reactor. (Dimensions are in centimeters.)

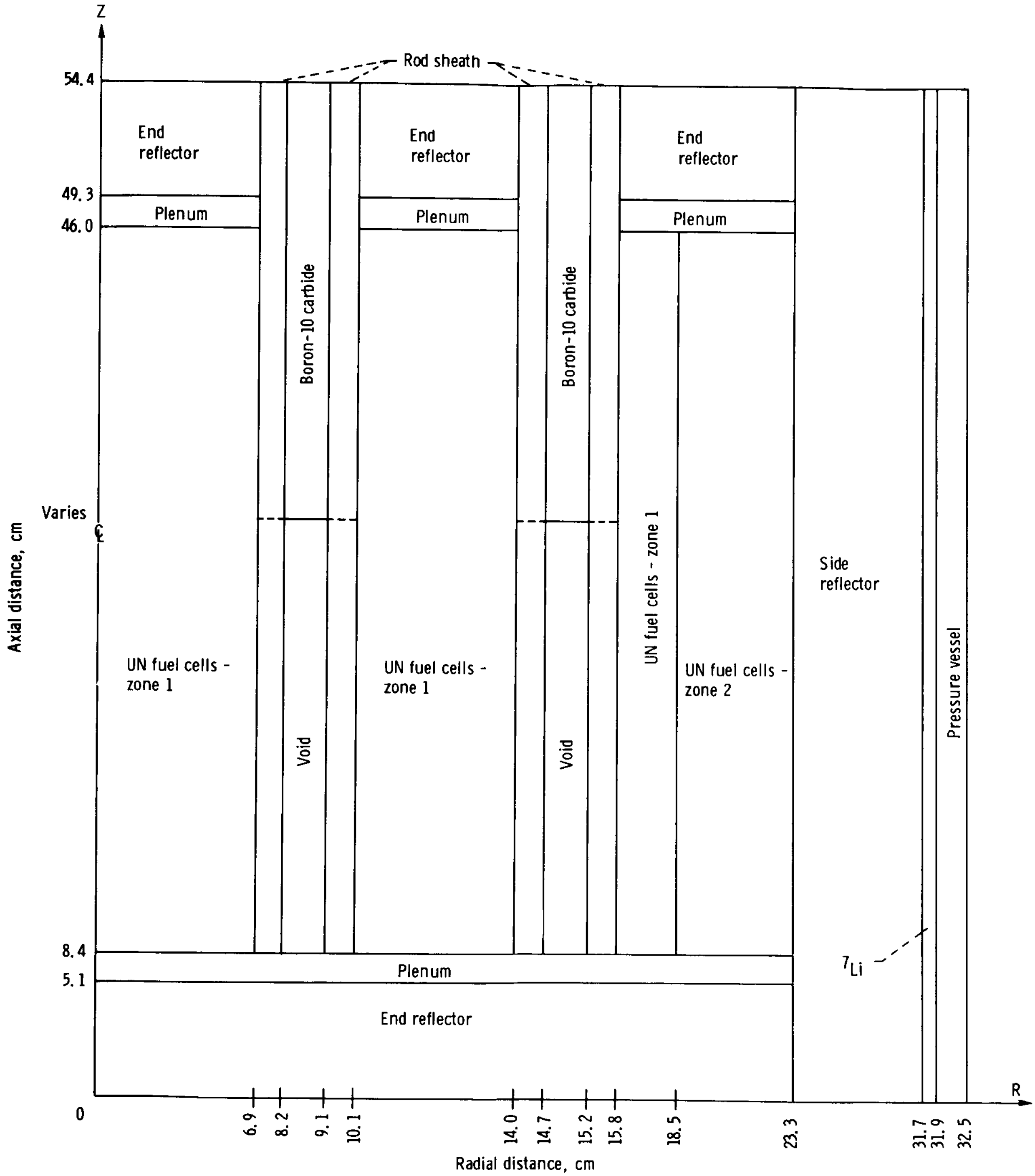


Figure 10. - RZ calculational model of rod-controlled reactor. Mesh intervals, 30 R and 35 Z.

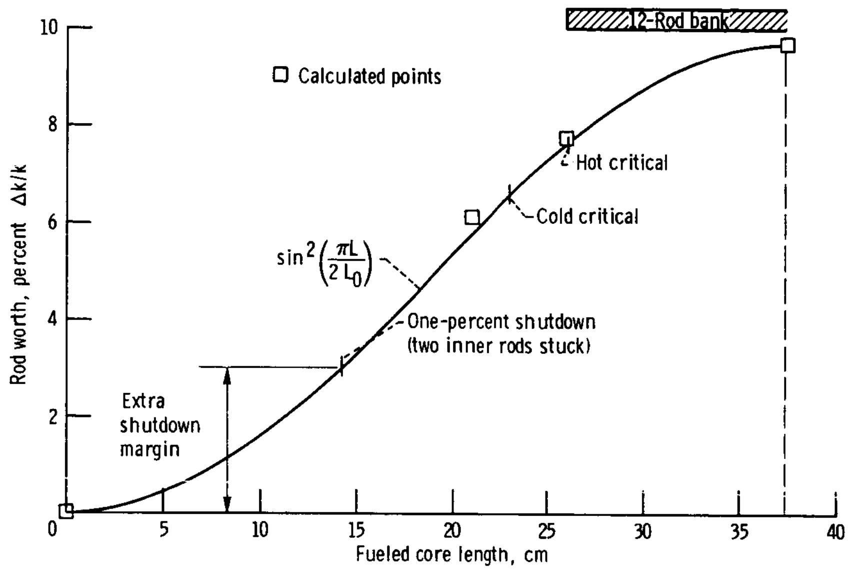


Figure 11. - Reactivity control for rod-controlled reactor.

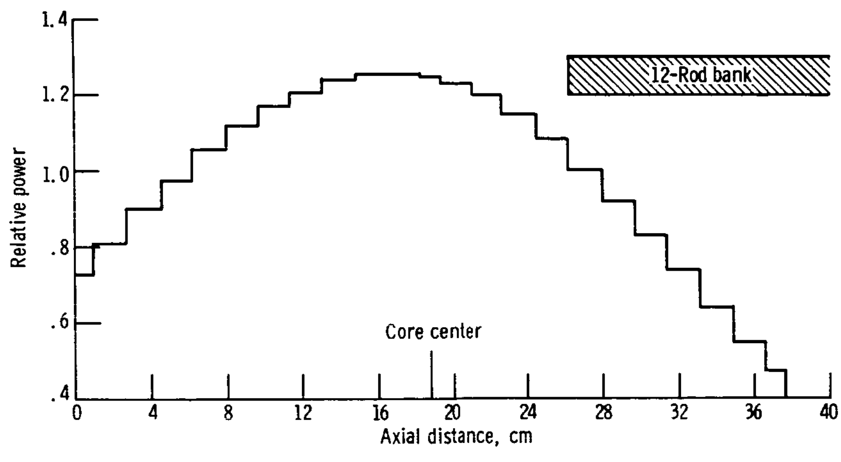
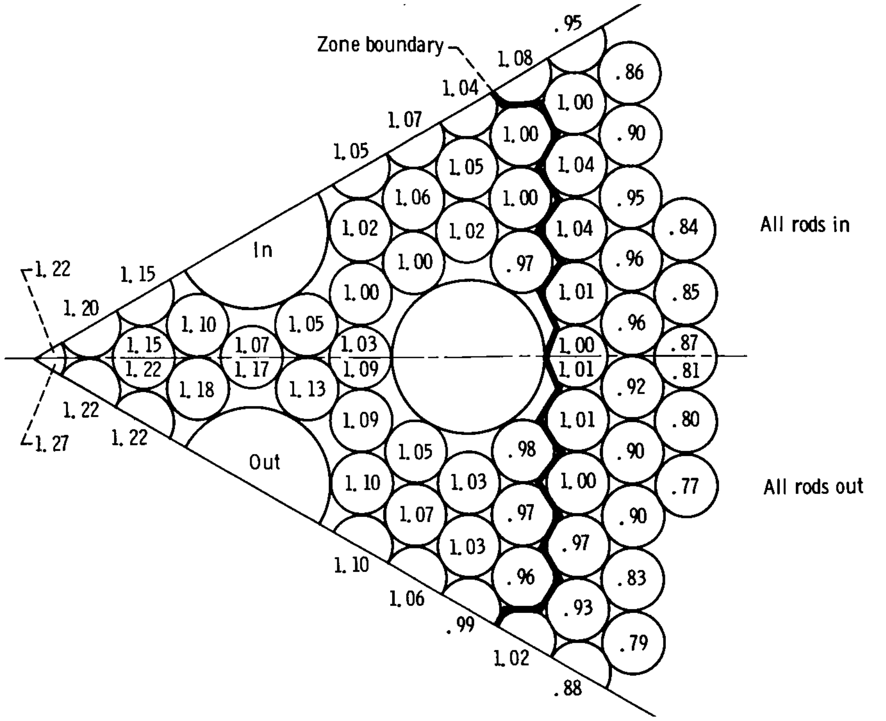
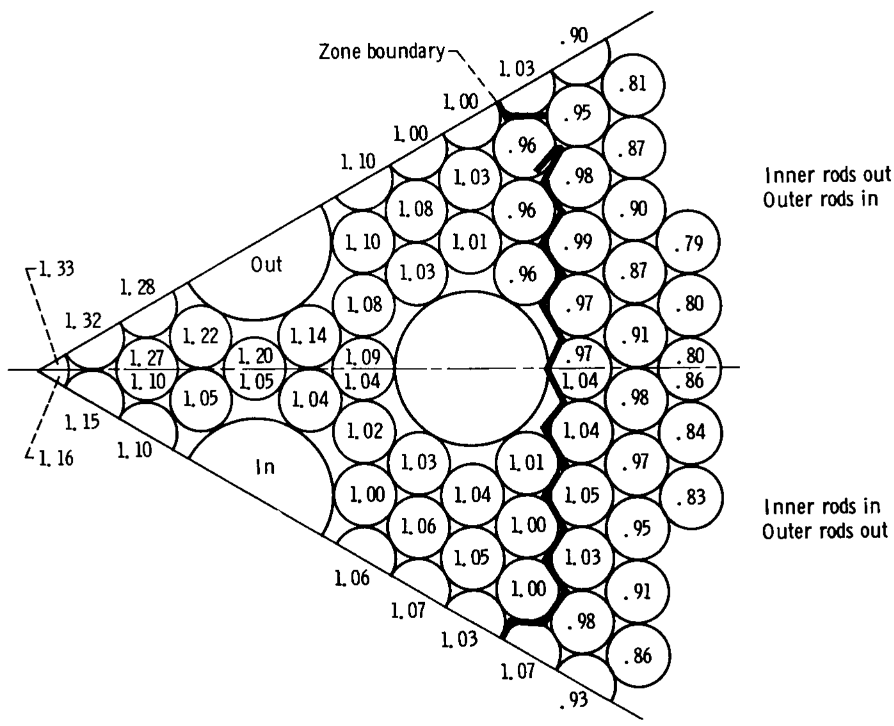


Figure 12. - Axial power distribution at hot critical for rod-controlled reactor.



(a) All rods in or all rods out.



(b) Rods operated as inner and outer groups of six rods.

Figure 13. - Radial power distribution for two-fuel-zone rod-controlled reactor. Center zone, 38.5 vol.% UN; outer zone, 42 vol.% UN.

Fuel zone	UN content in cell, vol. %
I	35.5
II	37.7
III	42.0

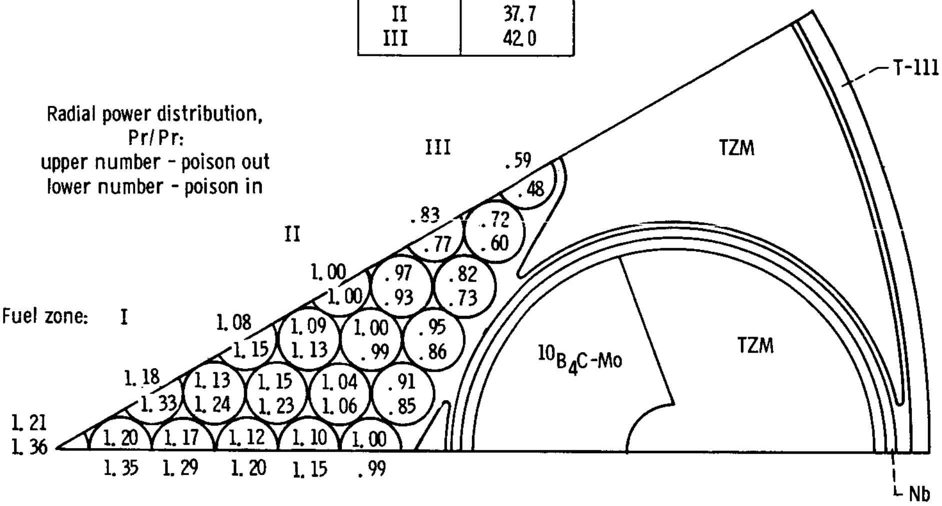


Figure 14. - 30° Sector of cross section of indented-drum reactor with drums in niobium dry wells.